

Wireless Sensor Network-based system for measuring and monitoring road traffic

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Abstract

Nowadays, the measure and classification of vehicles in road traffic is accomplished by inductive loops placed under the pavement. These inductive loops allow monitoring vehicle passing by means of different configurations which provide us a number of data in order to control several parameters of the traffic (vehicle speed, traffic congestion and traffic accidents, between others). The major objective of this paper is to analysis an alternative to magnetic loops: the Wireless Sensor Networks. Firstly, a state of the art about road traffic control is described. Secondly, an alternative system based on Wireless Sensor Networks is analyzed. Network architecture for this WSN will be specified. It is not a trivial task because of the hard constraints of the small devices which compose the WSNs. In previous papers [1], we have proposed a methodology that facilitates the WSNs design for supporting real time applications such as traffic control applications. This design methodology has been used in order to obtain a WSN that reaches the real time requirements of a monitoring traffic application for intelligent roads. In the short term, the aim is to define a simulation model based on the designed WSN. To conclude, we have introduced a section about possible future directions in the smart roads field.

Key words: smart roads, Wireless Sensor Networks, Performance in WSNs.

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1 Introduction

From a few years to this part, the proliferation of equipments in roads to monitoring traffic in real time has been evident. The most common problems that we can find in roads nowadays are huge; there are fearsome traffic congestions, which make lost a lot of time, money, health and environmental quality every day. All these things have influence on the population and on the planet.

The present paper tries to give an approach about the real-time data acquisition systems applied in roads as well as to introduce a solution allows to improve the systems related with the well-known "smart roads", by means of Wireless Sensor Networks (WSN).

Firstly, it will be describe the typical method to measure and classify vehicles by means of inductive coils. Secondly, it will be exposed an alternative based on WSN; this kind of networks offers a number of characteristics more advantageous than the offered by the old systems.

1.1 Road traffic

Nowadays, there are different system deployments that allow control road traffic. We can find a lot of approaches from point of view of transmission and reception of information:

- **Data acquisition stations and inductive coils:**

In these kinds of data acquisition systems to get data from road traffic is carried out by means of a few stations. These stations are placed in the protected boxes that we can see in the wings of the roads. Inside of these boxes, between other components there are a few detectors that receive the pulses from the inductive coils placed under the floor.

The inductive coils allow detecting the presence of vehicles over the road [14]. With this kind of systems (two coils placed successively) it is possible to get different data, as intensity, activity, congestion, average speed, average distance between vehicles and detection of vehicles driving in opposite sense [12].

- **Singposting System:**

The objective of these systems is to show information about all what is happening along the road to the drive. They are made by digital panels which show information needed for the safe and fluid traffic on the road. They connect to the most close data acquisition station by means of optical fiber. These data are transmitted to the Control Center in order to the users could always know what happens.

- **Weather stations:**

The deployment of weather stations is also usual in order to known and to prevent risky situations. These stations are equipped with a huge variety of sensors as thermometers, barometers, anemometers or hygrometers.

- **Tele-vigilance system:**

The monitoring centre can get knowledge about all what happens in anywhere of the road at real time by means of cameras deployed along the road. It helps to activate the emergency services in a few minutes.

The video signal can be transmitted to the monitoring centre by means of proprietary or TCP/IP protocol stack using Ethernet transceptor and optic fiber as transmission mean.



Figure 1: image captured by video camera.

- **Monitoring centre:**

It is the place where the management of data got from devices deployed along the road is performed. The monitoring room is connected to the communication network that includes the data acquisition stations. These stations transmit data using optical fiber switches between other devices.

- **Communication architecture:**

The networks deployed in order to support these kinds of data acquisition systems are usually built with optical fiber (monomode/multimode). These optical fiber networks are the base over which different protocols are working: Ethernet in link level, or TCP/IP in network and transport levels, as well as the applications needed in the higher level.

2 Measurement and classification of vehicles using Wireless Sensor Networks

As it is said before, the measure and classification of vehicles is performed by means of inductive coils situated under road floor which is able to get multiple parameters to analyze events produced over the road. However, these systems have several problems and disadvantages as their deployment, maintenance, high cost, and put into gear, between other. In this sense, the present paper proposes an smart system based on WSNs. The acquisition of knowledge about events produced is especially powerful by means of the micro sensors integrated in the nodes of this kind of network.

2.1 Wireless Sensor Networks

As said before, WSNs have appeared as a good alternative to inductive coils. Additionally, the nodes of a WSN have to integrate magnetic sensors in order to be able to collect events produced on the road floor. By addition of this kind of sensor and other few changes, a WSN can provide the same functionalities than a system based on inductive coils as well to offer a lot of advantages: low cost, easy and brief deployment, adaptability to multiple scenarios, versatility, reuse according necessities of public authorities [11], etc. These new characteristics differ the inductive coil systems from WSN, mainly because of the inductive coils are fix devices which cannot be easily transported from a place to other since they are usually under a thick layer of asphalt. Therefore, it is not feasible to use them for eventual situations, i.e. holidays or statistical studies, between others.

2.2 Operation principles

WSN are implemented using a number of innovative technologies like low-consumption microprocessors and radio transmitters, multiple kinds of sensors integrated in the same node, etc. These networks are made by a variable number of sensor nodes deployed over different places of the scenario as well one or more sink nodes that collect events detected by sensor nodes. Each sensor node has a magnetic sensor, a microprocessor, radio transmitter and battery cells [13]. The sensor nodes are usually placed along the wide of the road where the traffic wants be measured.

A comparative of deployment methods of each system is shown in following figures. Figure 2 shows the method to set inductive coils on the road, and figure 3 and 4 show different deployment scenarios for systems based on WSN whit magnetic sensor integrated into its nodes.

Measurements and procedures carrying out by the sensor nodes are processed and sent through radio link to sink node. The sink node is placed in a road side. This node has usually more resources, in terms of processor capacity, memory size or other peripheral devices (as GPS) than the sensor nodes deployed on the road. The sink node preprocesses data gathered from sensor nodes. If these data are considered important events, the sink node will transmit them to a server sited in the monitoring centre where the events will be interpreted by the applications of road traffic management. Transmission from sink node to server is usually carried out not only by cable networks but by wireless networks using protocols of mobile systems like GPRS or UMTS [8].

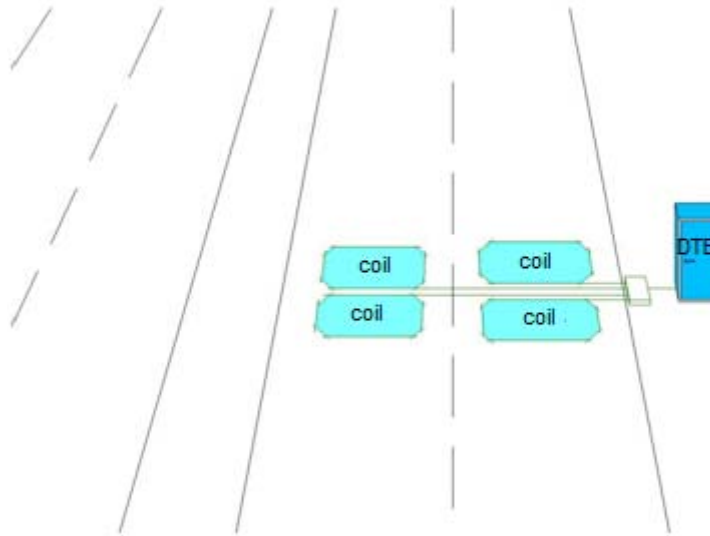


Figure 2: Scenario with inductive coils.

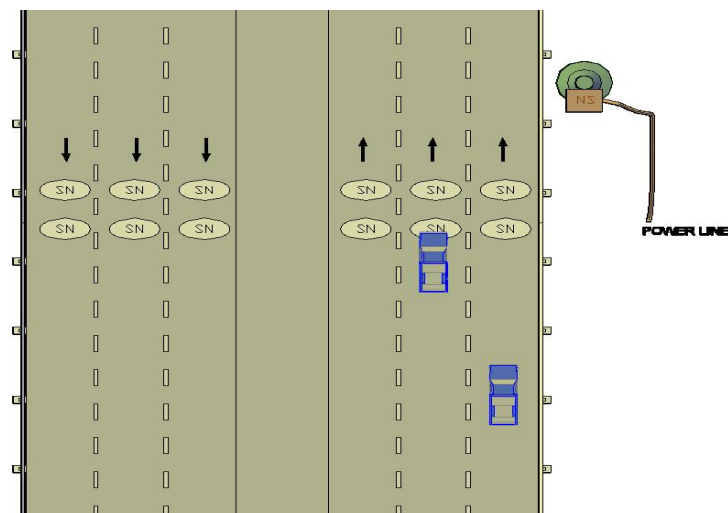


Figure 3: Scenario with sensor nodes.

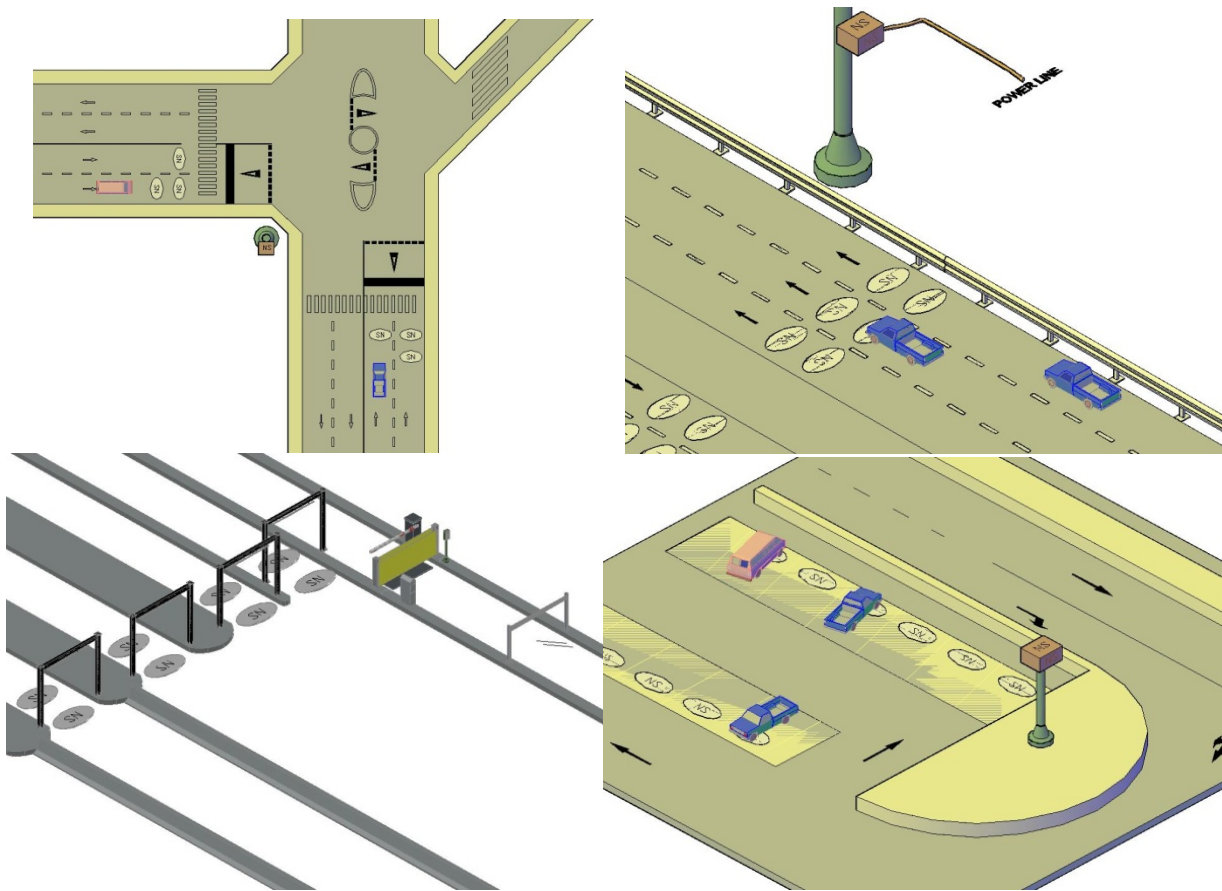


Figure 4: Example scenarios where WSN could be used: highways, intersections, parking and toll gates.

2.3 Wireless Sensor Networks and Inductive Coils: comparison.

Nowadays, the most used systems of traffic measure and classification are based on inductive coils that are deployment in number kinds of scenarios: toll road, highways, tunnels, shadow tolls, etc. On the other hand, the WSNs with magnetic sensors have appeared as a new paradigm of smart traffic control.

The inductive coils are active devices and, therefore, they have high energy consume. Sensor nodes are semi-active devices (they alternate between active modes and sleep modes) what reduces energy consume considerably since these can be supplied by means of small batteries or renewable energy systems.

The WSNs can be deployed in almost anywhere, even in those places where inductive coils aren't feasible to be deployed, as bridges and grade crossing, where it is needed to cut the floor to set the inductive coils.

The WSNs have been established as an economic alternative, since the inductive coils are expensive systems. As well, inductive coils solve partially the traffic problems raised from the great amount of vehicles that are driven by means of roads of the industrialized countries [11].

3 Network deployment in a smart highway

The deployment of a WSN in a smart highway presents challenges when compared to the use of inductive coils. Firstly, we face the design and implementation of a network architecture adapted to WSNs. This includes the choosing of both a topology and an adequate set of communication protocols capable of providing the necessary autonomy. Secondly, the stringent restrictions (mainly in power consumption and memory / processing capabilities) of WSN nodes strongly influence the task of making decisions on the network architecture.

Taking these premises as a starting point, we propose a strategy for the design of WSN with the aim of getting optimal performance in real time applications (such as the monitoring of road traffic). We start from the requisites of a smart highway to determine the minimum set of functionalities that have to be present in both the link and network layers of the communications stack. Then we propose a selection of WSN-specific protocols that comply, almost in its entirety, with this set of application-driven functionalities. Finally we will establish a network simulation model useful for defining the design decisions of the actual system to be deployed.

Inside next subsections we present a step by step description of a method to define a WSN whose aim is to support an application for measurement and classification of vehicles in smart highways. The simulation and testing models for these applications are out of the scope of the paper.

3.1 Requisites of a road traffic control application: description and analysis

Our considered road traffic control application does not require a very complex WSN, since it serves a sole purpose: detection of the vehicles driving through the controlled road zone. Each control point will be managed by a WSN which will send the detected vehicles data to the sink. The sink is connected, through a “conventional” network, to a server (e.g. using Web services and a TCP/IP network, see Figure 5) which hosts the decision algorithms that consider road traffic status and possible anomalies (e.g. traffic jams, vehicles moving in the wrong direction or at an inadequate speed). There may be many traffic control points and thus many WSN connected to the central server. This makes it necessary to have a network connecting the sink nodes, dimensioned to serve a considerable load of packet traffic as well as reliable and secure. This paper tackles the issues related to the WSNs infrastructure.

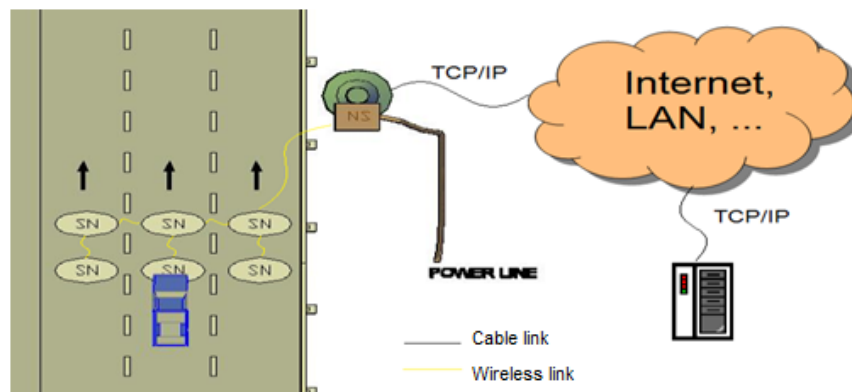


Figure 5: Network infrastructure for a vehicles measurement and classification application.

Although the complexity of the considered WSNs is low, the critical requirements of the application call the attention upon certain issues. Considering the infrastructure shown in Figure 5, we highlight the following ones:

- Topology and network dynamics: Network topology will be flat. This means that all the networks nodes will belong to the same hierarchy level, i.e., they will have the same functions and hardware components.
- Geographic information: sensor nodes must obtain geographic information (i.e. coordinates) to locate the detected events within the controlled zone (in our case, circulating vehicles). Commonly used methods for obtaining this information are based on GPS [2] or distributed localization techniques [3]. GPS-based localization methods are not adequate for WSN due to the high energy consumption they require and their high cost (each WSN may be composed of hundreds or thousands of nodes, and each of which would need to have a GPS transceiver). Thus, distributed localization techniques prove to be the most adequate for their use in WSNs, only requiring the deployment of some beacons which broadcast localization information. It must not be forgotten however that this adds certain traffic overload during the WSN initialization phase.
- Power consumption efficiency: This is clearly an important challenge for the application. It is important to have long batteries lives for the WSNs nodes (2 to 3 years at least) since each batteries change will require a temporal road traffic interruption. The key issue here is to balance as much as possible the energy consumption among all the network nodes in order to avoid the early depletion of a small set of nodes' energy.
- Sporadic events detection: In our case the events detection is sporadic since there is not a predefined pattern of vehicles traffic. Thus, packet traffic traversing the network will exhibit an event-driven behaviour. This traffic is generated in an aperiodic fashion due to the detection of critical events at impredecible points in time.
- Events detection reliability: The high importance of some of the critical events possibly detected by the application (e.g. a vehicle circulating in the opposite direction), makes it of great importance to have a high reliability level when detecting an event.

- Real-time requisites: The time elapsed from the detection of an event until its notification to the application has to be low in order for the information to preserve its usefulness.

3.2 Network layer

Taking into account the requisites that the application poses to the WSN (described in the previous subsection), we can identify the functionalities and capabilities to be supported by the network layer of the sensor nodes.

The first challenge that the network protocol has to face is the high topology dynamicity, mainly driven by three factors: faults, addition and mobility of the nodes. Also the high number of nodes is a significant issue to consider in the network layer. Traditional routing methods, which are based in point-to-point routes discovery, resources reservations along the path and alternative routes re-discovery when the topology changes, are not appropriate for WSNs: the initial delays observed in these methods are excessive for aperiodic packet traffic generation patterns with stringent delay requirements. Besides, it is not advisable to reserve resources for unpredictable and aperiodic traffic, since most of the time those resources will be underutilized. Even when traffic flows are periodic and continuous, the usefulness of these routing techniques in WSN is low because network dynamics will cause frequent service interruptions and the subsequent activation of routes recovery procedures. During the routes recovery process data may experience high delays to reach the sink, something not acceptable when dealing with critical-objectives applications (such as the one considered in this paper). Finally, mechanisms based on point-to-point routes establishment do not scale well since they present high overheads when discovering and recovering routes, and each node must store those routes' state tables.

To avoid the effects of topology changes, we propose to use a network layer implementing a localized routing mechanism. This type of routing mainly provides adaptivity to dynamic topology changes, since network nodes do not need to acquire WSN global information. As an immediate consequence, when topology changes arise due to the adding, failure or mobility of nodes, there will not be a significant amount of control packets. WSN nodes will be able to make localized routing decisions without previously establishing a route or obtaining global network information, thus greatly increasing network scalability and diminishing monitoring traffic. Moreover, this routing mechanism is suitable both for aperiodic critical traffic (event-driven traffic) and periodic traffic, because it is not necessary to establish routes and the recovery time is low.

On the other hand, network layer protocol has to provide a certain Quality of Service (QoS) level to the routed packets. In our WSN, QoS comes defined by two parameters: reliability and delay. Network layer will implement complex mechanisms to comply with the QoS objectives. To deal with minimum delays, mechanisms may be used that calculate distance to the sink depending on the route. To deal with the reliability, one can take advantage of the WSN-inherent routes redundancy, increasing the ratio of delivered packets thanks to the sending of duplicate packets through different routes.

3.3 Link layer

Not all the application requirements can be covered by the sole use of the mechanisms present at network layer, described in the previous subsection. It is necessary to implement certain MAC mechanisms inside the link layer of the protocol stack. MAC protocol should be able to perform tasks such as measurement the mean delay to the nearest neighbouring nodes, or calculating the frame loss ratio of each link to neighbouring nodes.

All the information that the MAC protocol obtains on links with neighbouring nodes can always be obtained by the network layer. This way it is possible to provide QoS based on real data related to the links states at each moment. To reach this goal, so-called inter-layer optimizations mechanisms have to be present that efficiently provide for the interchange of control information between different layers of the protocol stack.

3.4 Network and link layer protocols selection

Taking into account the mechanisms described in previous subsections, we present in the following the design decisions we have made regarding network and MAC protocols in order to best adapt to a road traffic control application. The protocol selection inside this subsection is based on an exhaustive state of the art study on mechanisms and protocols that can be found in [1].

Network layer protocols

We may find two network layer protocols, among those included in [1], which could be used in our WSN, namely: MMSPEED [4] and Directed Diffusion [5] (see Table 1).

MMSPEED

The routing mechanism implemented by MMSPEED is based on the geographic location of the network nodes. This increases the auto-adaptivity of the protocol to dynamic network topology changes. Besides, it is adequate for both periodic and aperiodic traffic patterns, since routing decisions are made based only on local information. To route

data packets a node only needs information on the links state and the geographic location of the near nodes (reachable within one or two hops range). Two direct consequences of this are: 1) routes establishment (and resources reservations) is not needed, and 2) the time to recover when a node fails is minimum.

MMSPEED also implements a multi-speed mechanism to support different maximum delays applicable to traffic subsets. This is very useful when dealing with multiple traffic classes (e.g. continuous flows, event-driven traffic with different delay requirements, etc.). In the case of smart highways applications, if sensors for the continuous monitoring of parameters such as temperature, wind strength or light intensity are present together with sensors for the detection of circulating vehicles, the multi-speed characteristic proves to be very interesting. Each of these sensors generates traffic with different traffic patterns and QoS requisites. MMSPEED also includes a method for dynamic speed compensation. Using it, packets routing may become more advantageous if it is detected that delay requirements are threatened for some traffic class. This somehow compensates for the inexact local information on which the routing is based, which does not include the whole network state.

Routing decisions in MMSPEED are also made taking the reliability requirements of traffic classes into account. Regarding the reliability domain, MMSPEED implements a complex mechanism that duplicates the packets sending them through several routes to the sink. To determine next nodes for a packet, MMSPEED takes into account the frame loss ratio of each link to neighbouring nodes. This information is directly obtained from link layer.

Directed Diffusion

Directed diffusion is a data-centric protocol directly related to the application. It implements a data-aggregation method to eliminate redundant information coming from different source nodes. This drastically reduces the number of transmissions with the following two direct consequences: first, nodes batteries last longer, improving network lifetime. And second, since there are a much lower number of packets traversing the network, links are less congested, especially those nearest to the sink. Directed diffusion is said to be related to the application because it has to deal with the data types of the application to perform the aggregation algorithms.

Directed diffusion is based on a query-driven model. Using this, the sink asks for data to a certain sector of the WSN, broadcasting its interests in the required information types. Packets generated due to events detection flow to the sink through routes established during the initial interests-broadcasting phase. Each packet is routed using several routes in order for the packets to reach the sink with higher probability.

The aforementioned Directed diffusion mechanisms may optimize the routing considering issues as reliability or robustness. However, Directed diffusion does not consider QoS parameters such as the maximum allowed delay for real time traffic, or different resources allocation for distinct traffic classes.

Table 1 below shows a comparison of the main characteristics of Directed diffusion and MMSPEED.

Table 1. WSN routing protocols: comparison

	Network topology	Traffic pattern	Data aggregation / fusion	Traffic guarantees	Traffic classes support	Supported network dynamics	Resources reservation	Scalability
Directed diffusion	Flat	Query-driven and event-driven	Yes	Reliability	No	Limited	Yes	Medium
MMSPEED	Flat	Event-driven and continuous	No	Reliability and real-time	Yes	Limited	No	High

Link layer protocols

To select link layer protocols we have to consider some network protocols characteristics, described in the following paragraphs.

First of all, selecting a MAC protocol that complements MMSPEED is not easy. Inside the MMSPEED specification, a 802.11e protocol extension is proposed to support all the mechanisms implemented at network layer. Among these, the most complicated one to be considered by the lower layer is the priorities scheme. We propose to use the Z-MAC protocol [6] as an alternative to 802.11e (see Figure 6). To be completely compatible with MMSPEED, Z-MAC needs some additional features. However, we consider it as an excellent starting point, because it includes a very adequate priority mechanism. Moreover, Z-MAC includes a hybrid MAC protocol that behaves differently when facing with different content levels: a low contention level makes it behave as CSMA, and a high contention level makes it switch to a TDMA-like behavior. In addition, Z-MAC has to be capable of associating each MMSPEED traffic class with an appropriate link-layer priority level.

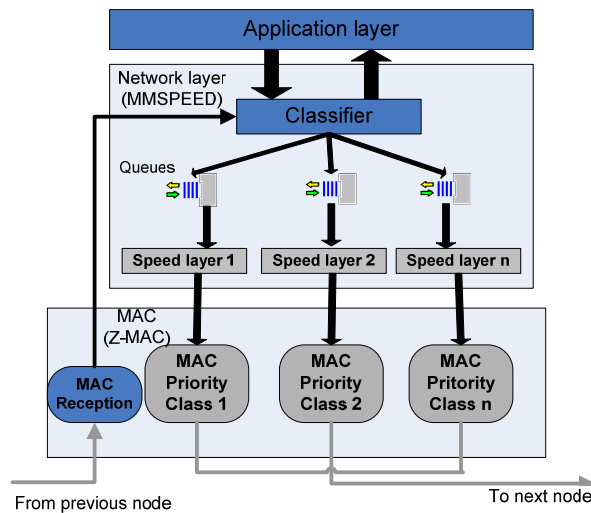


Figure 6: Internal structure of the priorities mechanism.

In addition to what has been said, Z-MAC includes a very efficient contention method capable of eliminating unnecessary backoff delays. Another interesting Z-MAC characteristic is its ability of quickly adapting to topology changes.

B-MAC [7] is another MAC protocol that could be used in our WSN scenario. It includes very interesting mechanisms to highly optimize the WSN operation. B-MAC has simple design and implementation together with a great flexibility, and it offers support to multiple service classes to be used in almost any scenario. However, B-MAC cannot offer QoS guarantees to data transmission.

For a comparison of Z-MAC and B-MAC see their main characteristics in Table 2.

Table 2. WSN MAC protocols: comparison.

	<i>Data aggregation / fusion</i>	<i>Scalability</i>	<i>Priority mechanisms</i>	<i>Energy-preserver</i>	<i>Contention algorithm</i>
B-MAC	No	High	No	Yes	CSMA
Z-MAC	No	High	Yes	Yes	Hybrid (CSMA – TDMA)

4 Intelligent Transport Systems and Smart Vehicles

In previous sections, a monitoring traffic system based on WSNs has been proposed. It has been defined several important points that characterized a WSN made to monitoring traffic. The study included in this paper has begun with a review of requirements of traffic control applications and, from there, several link and network protocols have been selected according to the behavior of the events detected by the sensors as well as the network topology.

To conclude, it will be described a smart application to manage traffic in which the WSNs could be useful in the next future.

4.1 Intelligent Transport Systems (ITS)

These systems are a set of information, communications and technologies for vehicles and infrastructures focused on the transport. In the last years, they have acquired a great importance since nowadays ICTs allow transmitting information to anywhere in real time [9].

4.2 ITS Characteristics

Regarding to inter-city transport, SIT applications would be those concern to the transport by road that provide information about traffic and travels. These applications allow managing the public transport, traffic road, as well as driver assistance.

In this sense, SIT applications offer useful information about the best routes to the destination according to different factors (congestion, road surface state, accidents, etc). This functionality is achieved by the information provision, in real time, about state of the selected routes and their alternatives. All this information can be offered by means of a accurate vehicle classification using WSNs.

4.3 ITS applications

The application of ICTs to the road transport allows talking about “smart roads” which are those ways with information systems working in real time. Smart roads make available, for example, control and regulation in accesses to the cities, information captures regarding to measurements of traffic intensity, speed and incidents, linear control of the route, control of incomes for the route, information about itineraries, help service or electronic payments (gate tolls) (see figure 7) [9].

However, the smart road systems need vehicles integrating devices which allow interaction with the smart environment. In this sense, it is not only necessary to develop vehicles being able to response to the environment events but also to understand and to foresee them. Therefore, mechanisms for smart adjustment as actuators or robotic devices have to be developed what make possible smart vehicles able to modify parameters such as direction, gear, breaks, and mirrors, between others, which will be controlled by a central computer like the brain of a great organism. In fact, car industry has begun a number of projects to carry out smart vehicles developing prototypes that integrate sensor nodes. Other examples of smart applications for vehicles are systems to throw alarms in case of changing direction in an abrupt way, systems to analyze road signs, pedestrian detection, speed control, driver control, etc.

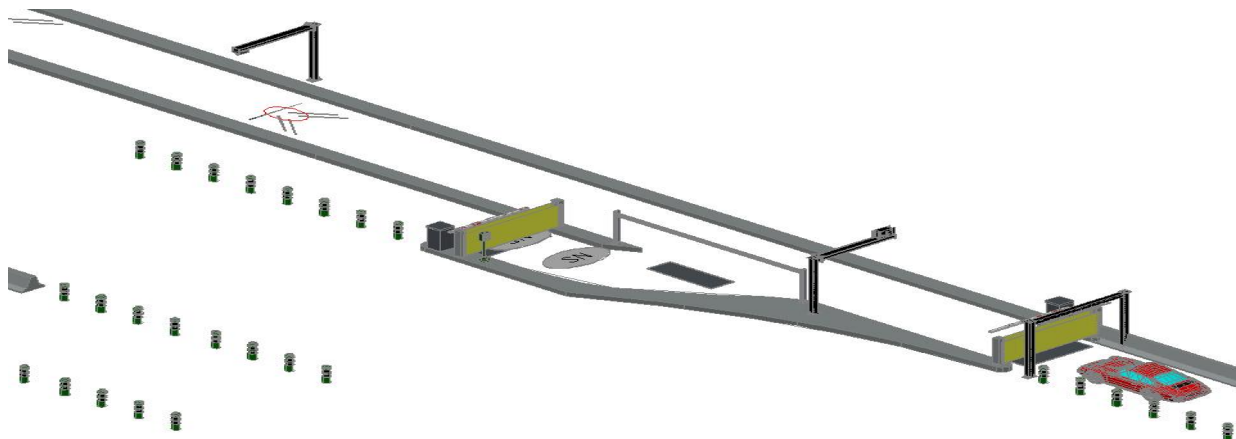


Figure 7: Toll gate with wireless sensors.

5 Conclusions

Nowadays, road traffic is an important problem in a lot of industrialized countries. This fact make essential to build a road and transport system characterized by high dynamicity and low congestion and incidents. In this paper, a new system of traffic control based on WSN has been proposed. The advantages of this new technology applied to the traffic control allow designing and developing systems with a high level of autonomy and intelligent. The capacities of these kinds of system to manage and get acknowledge about traffic are huge.

From these facts, this paper has been focused on analyzing and defining a system to measure and classify road traffic based on WSN of which sensor nodes integrate magnetic sensors. This system has been proposed as alternative to old inductive coils deployed in almost all roads in order to carry out a basic traffic control. The WSN has a great advantage respect to inductive coils: it can be deployed easy and quickly. However, the complexity of a WSN requires analyzing and designing a network architecture (that includes a communication protocol stack, the physical data transmission, the topology, etc.) suitable to the small devices (sensor nodes) that made a WSN. In this sense, the main challenge is to achieve an operation mode according to the strong resource constraints of the sensor nodes: energetic, computational, memory, etc. In this paper, a WSN with a flat topology has been proposed, in which all sensor nodes have the same functionalities and resources. In this way, a protocol stack has been considered in order to establish a good data interchange between the network nodes: MMSPEED for network layer and Z-MAC for link layer. Nowadays, the researcher team integrated by the authors of this paper, between other, is carried out the

design of a simulation model that extrapolate in a high fidelity way a WSN for measurement of vehicles in several contests: conventional roads, highways, toll gates, parking, etc. Once we had gathered enough data from the simulation model to do a depth study, field tests will be carried out over a real scenery.

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